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The Relative Effects of CW and RP Lasers on Composites and Metals

George P. Mueller

Directed Energy Effects Branch
Condensed Matter and Radiation Division

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DoD aircraft structural materials include both metals, primarily aluminum, and composites, primarily graphite/epoxy. The effect of lasers on these two materials is considerably different because of the large differences in some of their thermal properties. There are also significant differences depending on whether the laser irradiation is due to a continuous wave (CW) laser or a repetitively pulsed (RP) laser. Using the one-dimensional thermal response code FLIKER the effects of both CW and RP irradiations on aluminum and graphite/epoxy were modelled. Two classes of effects were examined: the immediate effects during the irradiations and the post irradiation damage effects.

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CONTENTS

THE RELATIVE EFFECTS OF CW AND RP LASERS ON COMPOSITES AND METALS

Introduction

We have calculated the relative effects of continuous wave (CW) and repetitively pulsed (RP) laser irradiations on a metal (aluminum) and a composite (graphite/epoxy). The total energy deposited per unit area is the same for these irradiations, so that the differences in the responses of the materials are caused by the different power levels and pulse forms. After describing the thermal properties of the materials and the details of the irradiations, we will examine the effects of the irradiations, both the immediate effects that appear during the irradiations and the damage effects that remain afterward.

Thermal Properties

All of the thermal properties for the graphite/epoxy (gr/ep) were taken from Menousek and Monin [1]. The use of these properties in simulation codes has been discussed by Griffis, et al. [2], and Mueller [3]. The thermal properties of the 2024 aluminum were taken from Touloukian [4]. Simple linear fits were made for the temperature dependence of the specific heat, density and thermal conductivity of the aluminum, but these are in good agreement with the data. In Fig. 1 we show the specific heats of the composite and the metal as a function of temperature. The complicated structure that appears in the composite specific heat curve is a reflection of the pyrolysis of the epoxy. Once the composite reaches 510°C the epoxy is completely pyrolyzed. Whenever the composite is heated above 510°C and then cooled, as may happen between pulses during a RP irradiation, we assume that the composite specific heat follows the second, pyrolyzed gr/ep curve, as shown in Fig. 2. During any reheating of the composite this second curve would be followed.

Each sample was taken to be 0.5 cm thick. For the density of aluminum we used 2.71 g/cm^3 [4]. The density of the gr/ep [1] was taken as 1.506 g/cm^3 up to a temperature of 510°C, after which it drops to 1.084 g/cm^3, due to the loss of the epoxy. The density of pyrolyzed gr/ep is taken as 1.084 g/cm^3 at all temperatures, as shown in Fig. 3. The aluminum melts at 660°C with a heat of melting of 377 J/g [4]. The graphite fibers sublimate at 3320°C and the heat of sublimation is 43 kJ/g [1]. Fig. 4 shows the thermal conductivities of the two materials. We note that, while the metal and composite specific heats and densities are not that dissimilar, the thermal conductivities differ by two orders of magnitude. This is the source of the large differences in the response of the two materials to the various laser irradiations.

Finally, Fig. 5 shows the decrease in tensile strength of the aluminum [5] and the graphite/epoxy [6] as a function of temperature. Each of the curves has been normalized to the tensile strength of that material at 20°C. There are two curves for the gr/ep [6]: the axial curve pictures the tensile strength in the plane of the fibers, and the transverse indicates the tensile strength across the plies. The transverse tensile strength is much lower because it is entirely due to the tensile strength of the epoxy.

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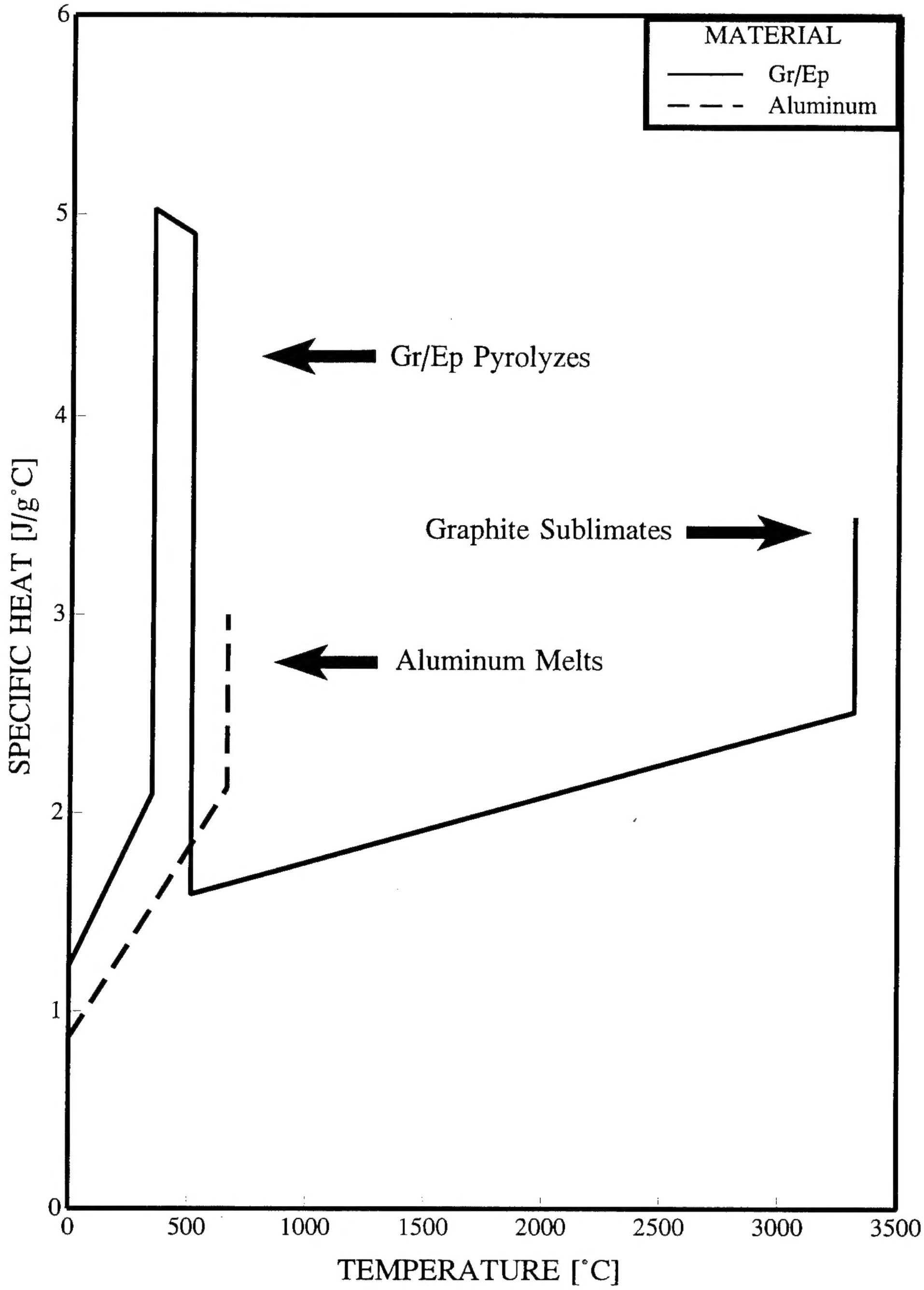

Fig. 1 — The specific heats of aluminum and graphite/epoxy

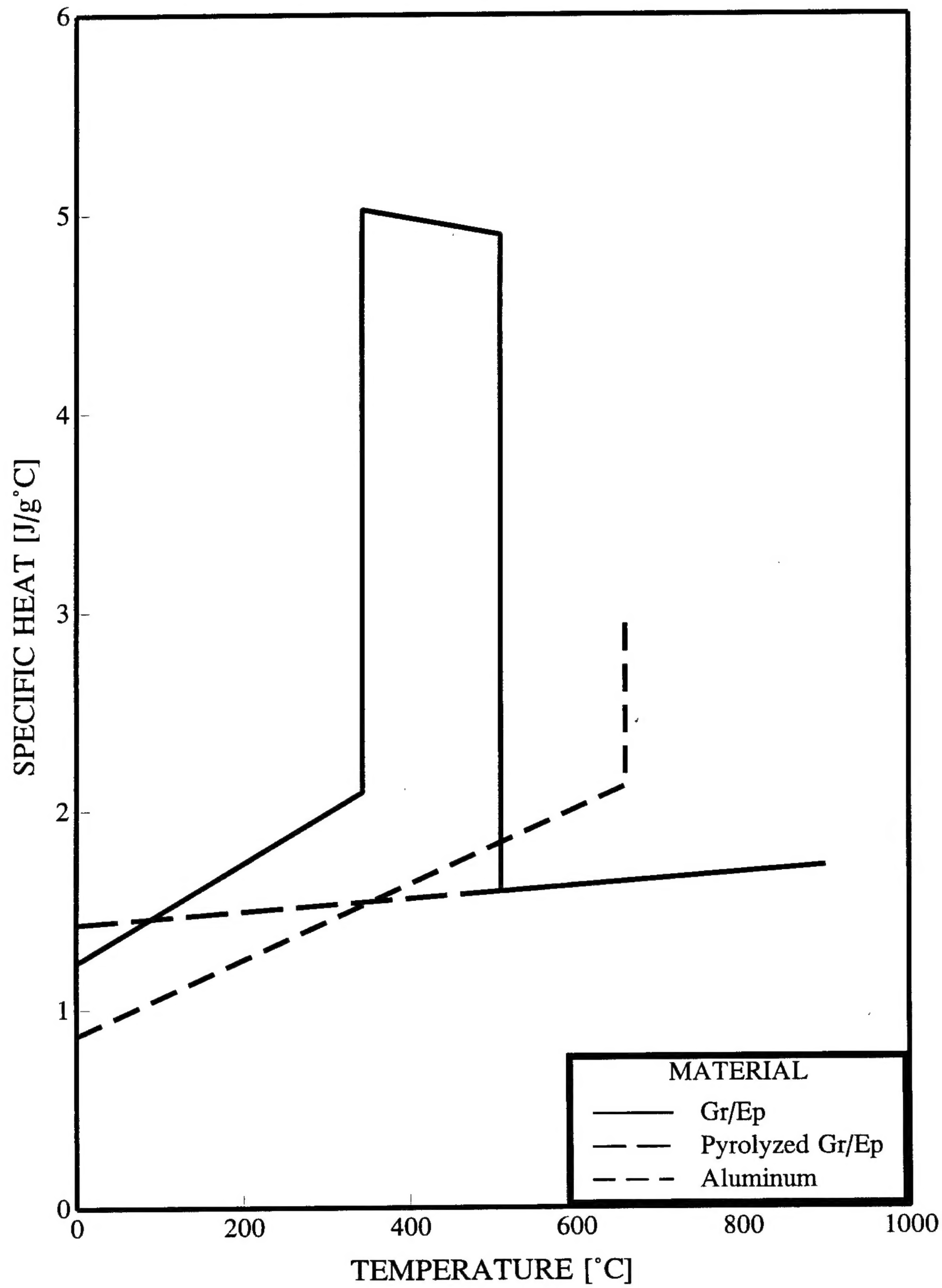

Fig. 2 — Details of the specific heats of aluminum and graphite/epoxy

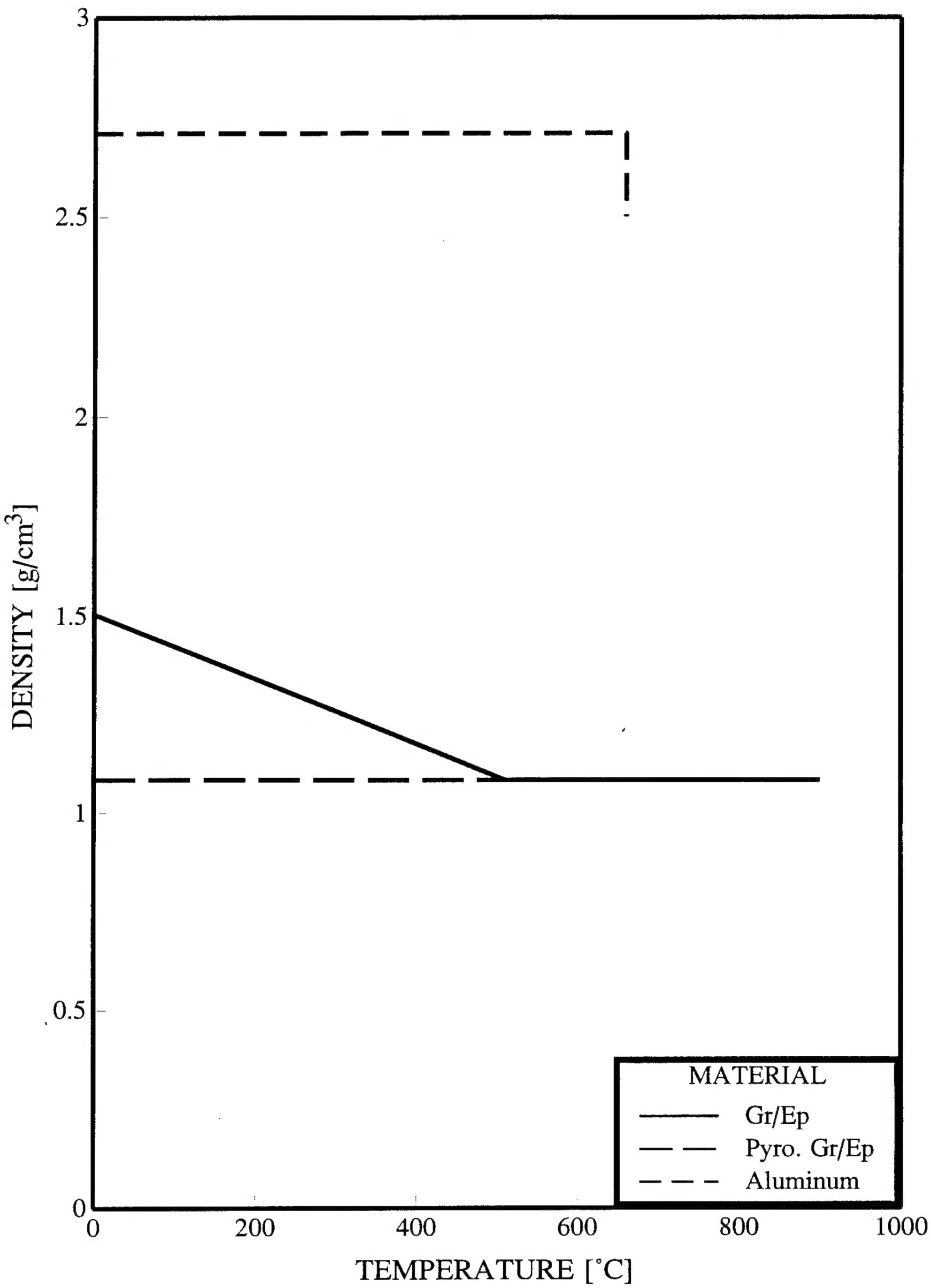

Fig. 3 — Density of aluminum and graphite/epoxy

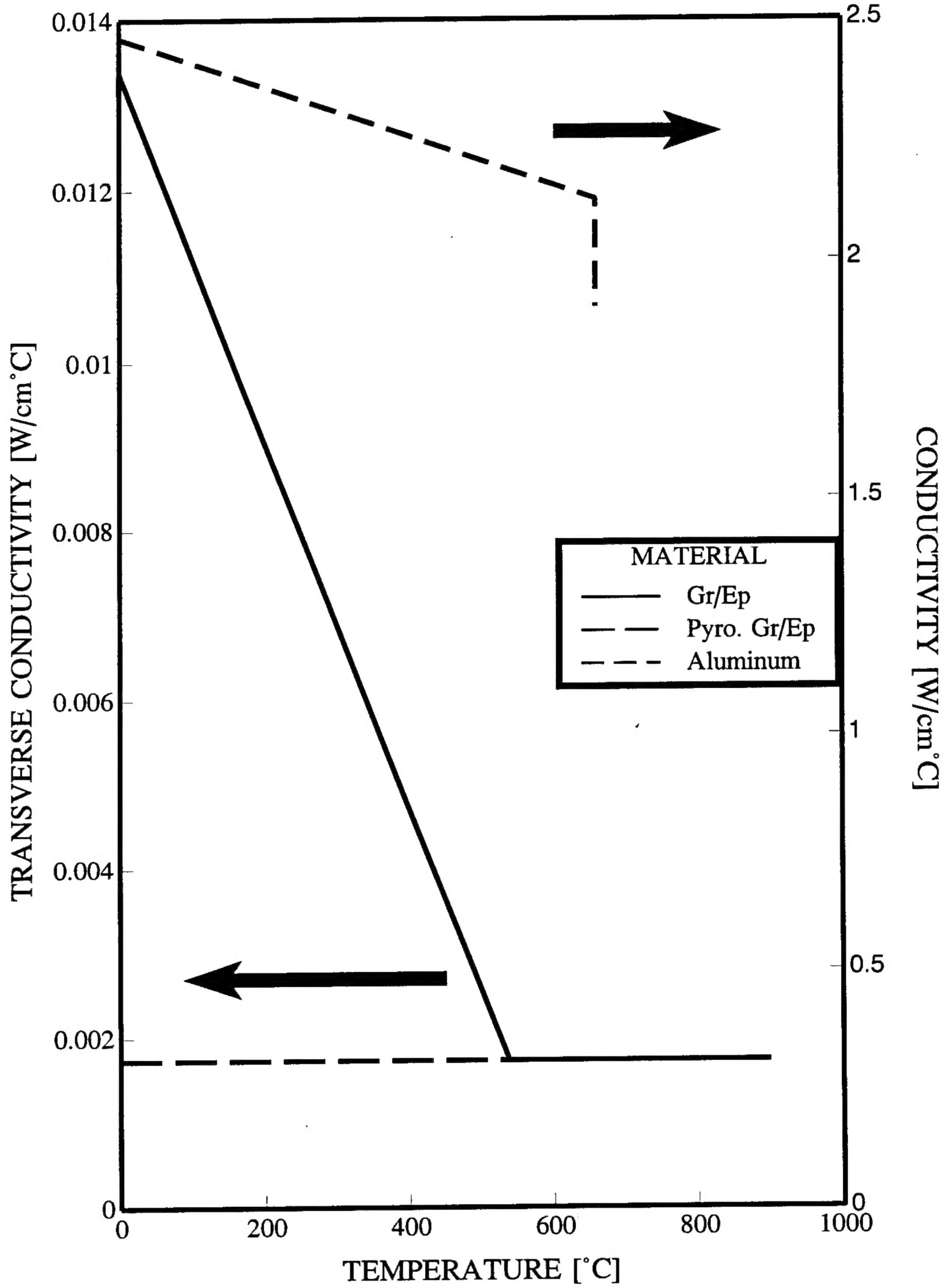

Fig. 4 — Thermal conductivity of aluminum and graphite/epoxy

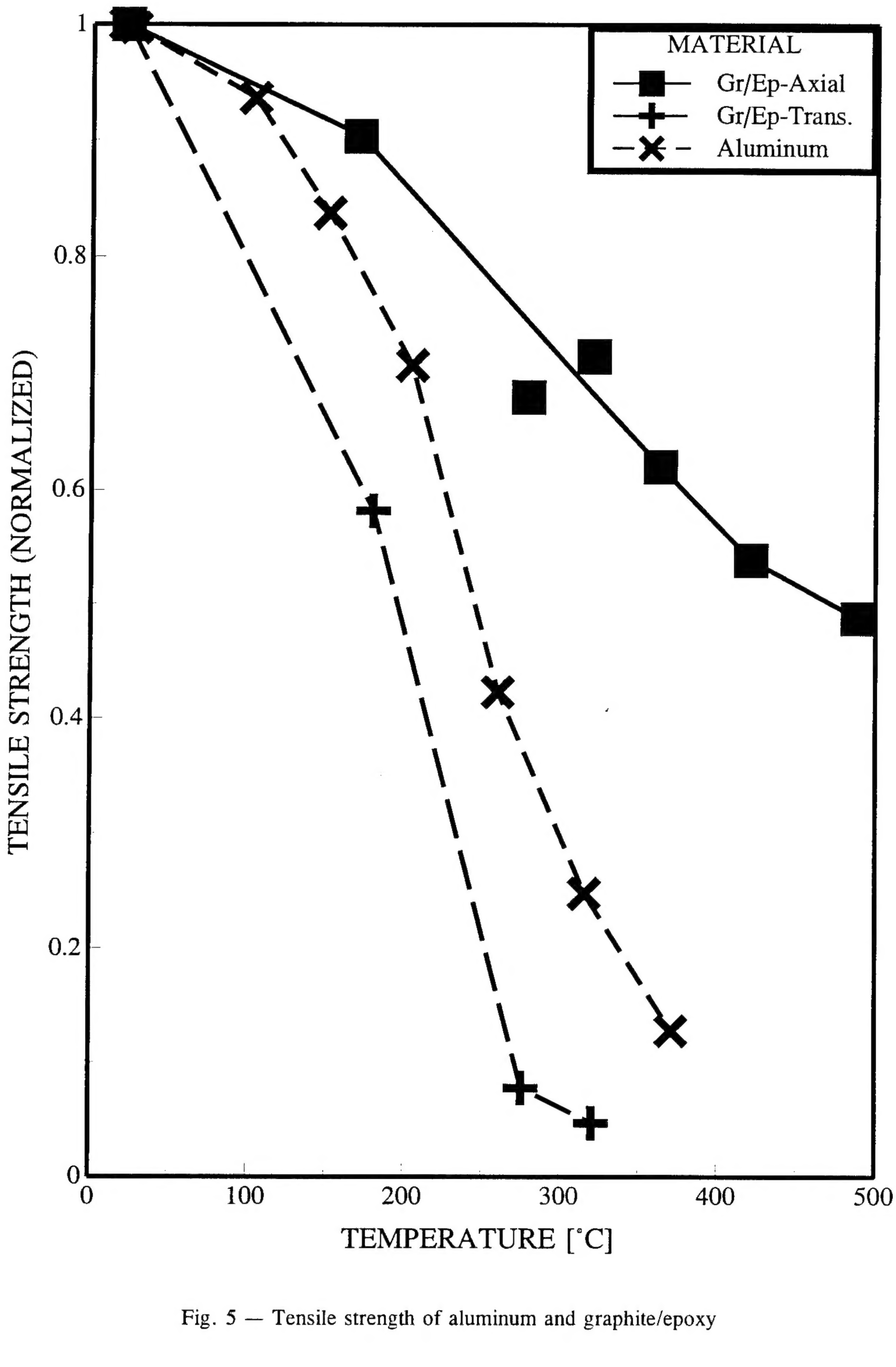

Fig. 5 — Tensile strength of aluminum and graphite/epoxy

Computer Modelling and Irradiations

The basic CW irradiation was 2 kW/cm^2 for one second, for a total of 2 kJ/cm^2. For comparison, we also simulated a 4 second irradiation at 0.5 kW/cm^2, which deposits the same energy. (As a shorthand notation for the CW irradiations, we will use CW(P,t) to indicate an irradiation of t seconds at a power level of P kW/cm^2.) The RP irradiation consisted of a one-second burst of 100 13-microsecond pulses. The laser power was 1.54 MW/cm^2; the total energy deposited is again 2 kJ/cm^2. All the irradiations were started with the materials at 20°C. The computer code FLIKER used for these calculations was developed by the author and has been described elsewhere [3]. The simulation was one-dimensional, so the model of the irradiation was equivalent to a flood-loaded sample in an actual experiment.

We assumed an air flow of mach 0.3 across the front of the irradiated materials, so that molten aluminum and any loose products of the composite pyrolysis would be carried out of the laser beam. Because small bits of fiber would be blown away during an actual irradiation of the composite, a lower value for the heat of sublimation should probably have been used, but we used the nominal value. The computer program includes both radiative and convective losses from the heated surface, but they were not significant at the power levels modelled in this effort.

The wavelength of the laser irradiation was taken to be the 10.6 micron CO_2 line. The only significant effect of the wavelength on these calculations is the absorptivity of the two materials at that wavelength. For the gr/ep we used an absorptance of 0.92 [2]. The value for aluminum is more difficult to obtain. Clean, polished aluminum has an absorptance of 0.03-0.05 at 10.6 microns [7]. Aluminum painted with ordinary MIL-SPEC paints absorbs nearly 90% of the incoming power, due to charring of the paint. During a RP irradiation, the surface is covered with molten aluminum (any paint present is blasted off), which has an absorptance of approximately 0.2 [8]. As a compromise, we used a value of 0.2. Even if one assumes MIL-SPEC paint in the CW case and an absorptance of 0.9, the large amount of energy absorbed would quickly lead to the melting of the aluminum and an absorption value of approximately 0.2. For a much lower power irradiation, a different value would have to be used.

Results: Effects During the Irradiations

Figure 6 shows the results of the three irradiations on aluminum immediately after the end of the irradiations. In the RP case the first few microns of the aluminum are at the melting temperature, due to the high instantaneous power of the RP laser. It is instructive to re-examine the temperature profile in the aluminum shortly after the end of the irradiation; Fig. 7 shows the profiles one second after the end of each irradiation. The high thermal conductivity of the metal leads to a uniform temperature across the 0.5 cm sample. There is slightly less energy remaining in the metal in the RP case, because some of the incident energy went into melting the surface material, which was then blown away by the air flow. But all in all, we conclude that the nature of the irradiation doesn't matter; only the total energy deposited is significant. At our imposed level of energy deposition--2 kJ/cm^2--all of the irradiations leave the metal in a weakened condition, due to the loss of tensile strength with elevated temperature.

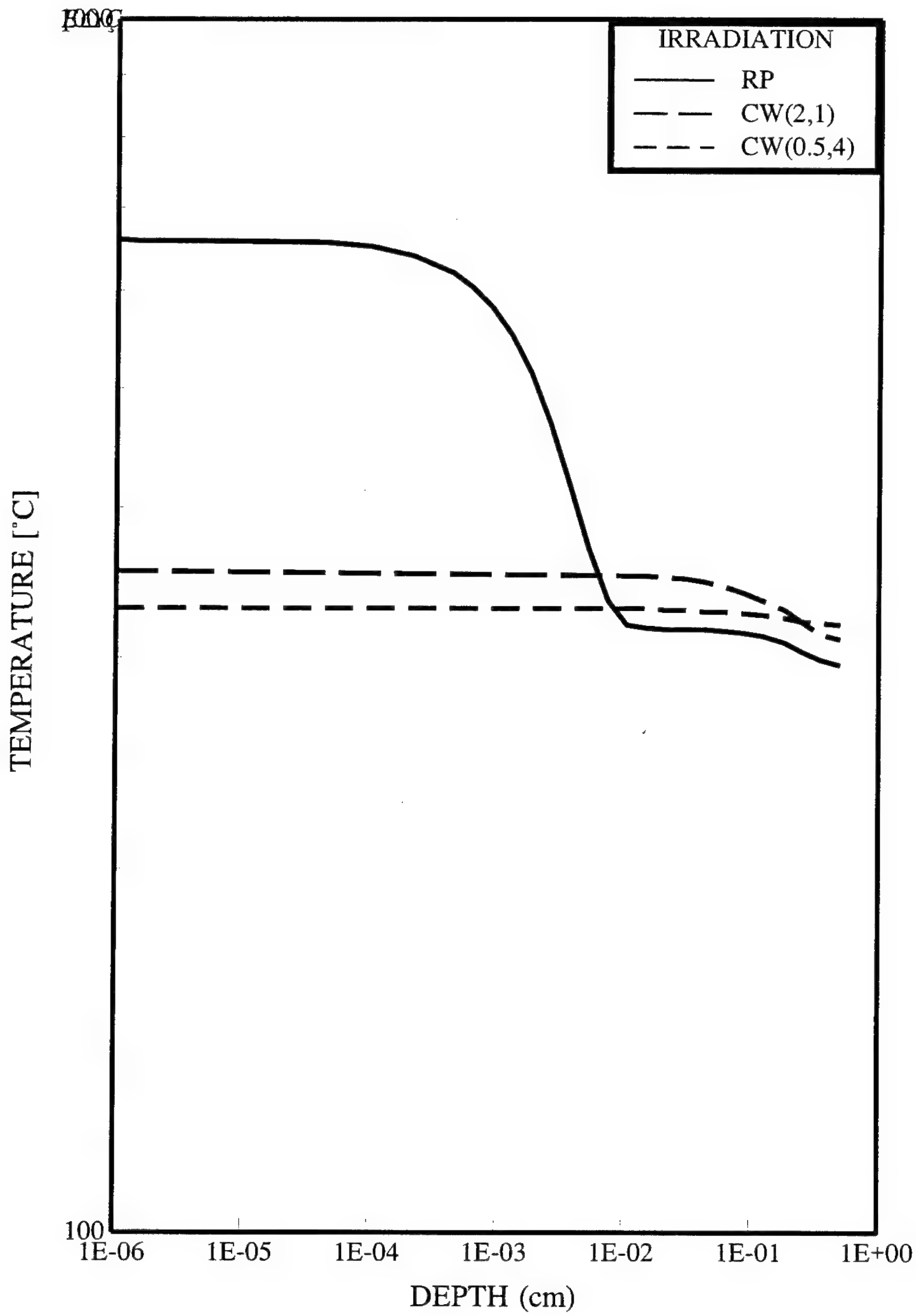

Fig. 6 — Temperature profiles in aluminum samples at the end of the irradiations

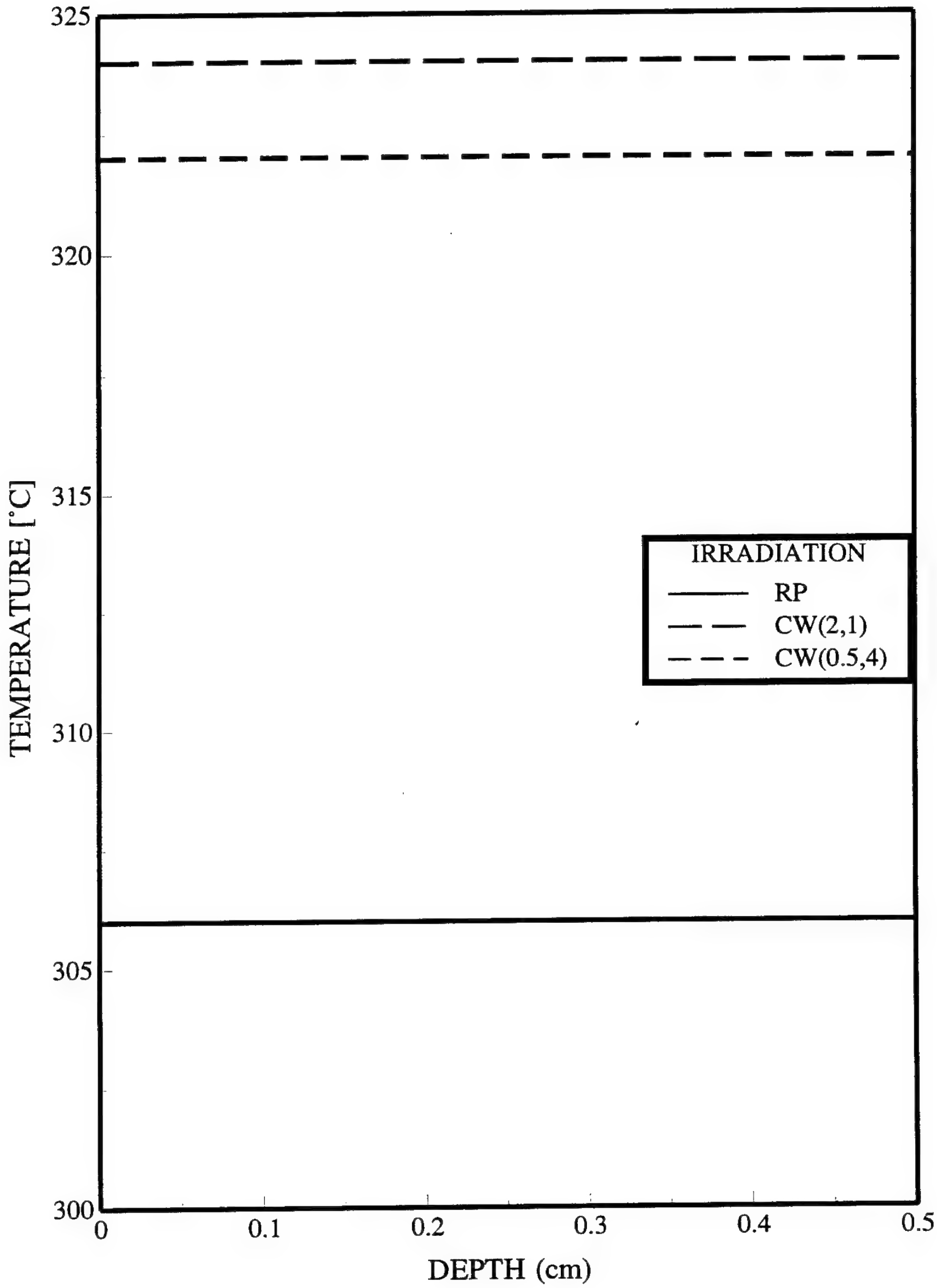

Fig. 7 — Temperature profiles in aluminum samples one second after the end of the irradiations

The situation is much more complicated in the case of the gr/ep; Fig. 8 shows these results. Immediately after the end of the irradiations, the surfaces of all three samples are at or near the sublimation temperature of the graphite/epoxy. In the RP case, the bulk of the material is at a much lower temperature than in either of the CW cases. The relative lack of damage from the RP irradiation is due to the extremely low thermal conductivity of the gr/ep. As the 1.5 MW/cm^2 pulse strikes the surface, the resultant heat stays at the surface. After only 25 nanoseconds of the first (13 microsecond) pulse, the surface is heated to the sublimation temperature of the graphite fibers. As the laser pulse continues to impinge on the surface, almost all of the energy goes into vaporizing the graphite. At the end of each pulse, there is little residual heat in the composite. In the case of the CW(2,1) irradiation, the results are very different: there is less ablation of the surface and considerably more energy is left in the material. Even more striking is the result of the lower power CW(0.5,4) irradiation. There is no ablation in this case, but much more residual heat in the composite.

These notions are more easily visualized in Fig. 9, which represents the same materials one second after the end of the irradiations. With the crude assumption that the specific heat of the gr/ep is constant, rather than as shown in fig. 1, the area between the curves in Fig. 9 and the ambient 20°C level is a rough measure of the energy that remains in the samples at the end of the irradiations. In the RP case most of the incident energy is lost from the sample in the process of vaporizing the graphite fibers. In the CW cases, especially in the lower fluence CW(0.5,4) case, most of the energy is retained in the samples, where it gradually--due to the low thermal conductivity--flows deeper into the material. These time-delayed damage effects are examined in more detail in the next section.

A few caveats should be offered. An actual irradiation would not proceed as simply as our model indicates. Some of the graphite fibers would be freed by the irradiation and removed by the air flow, so that more energy than shown would likely be available to produce damage in the material. Further, we assumed a very small optical depth for the CO_2 laser impinging on the graphite/epoxy. As long as the epoxy is still present in the RP case, a larger optical depth would make little difference, but after the epoxy pyrolyses, part of the beam is likely to pass through gaps in the fibers. On the other hand, once the epoxy has pyrolyzed, there would be relatively little thermal conduction between the fiber layers. Our one-dimensional model of the irradiation of the graphite/epoxy must be viewed as fairly crude. Nonetheless, the major conclusions should still be confirmed by a more detailed simulation or an experiment.

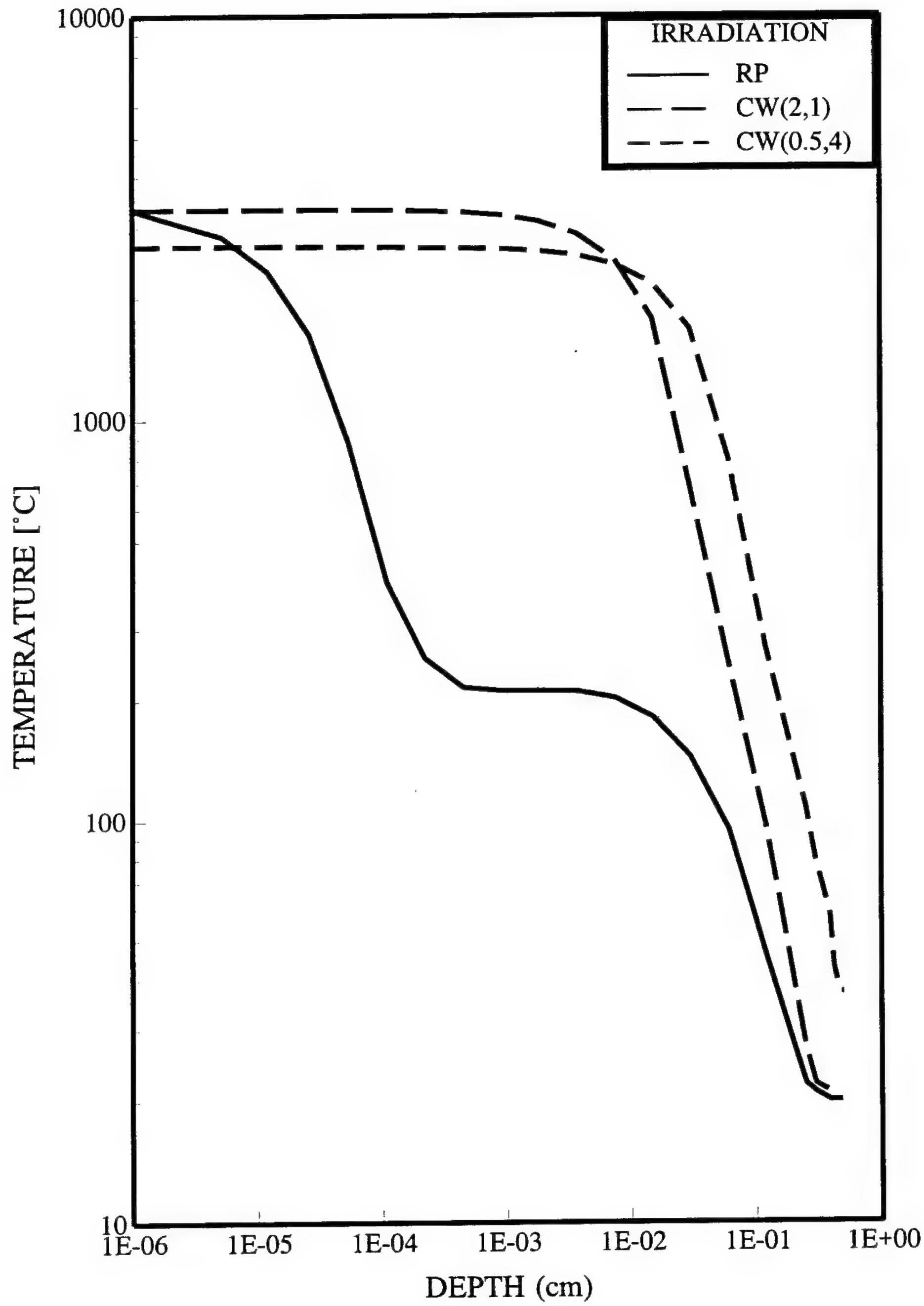

Fig. 8 — Temperature profiles in graphite\epoxy samples at the end of the irradiations

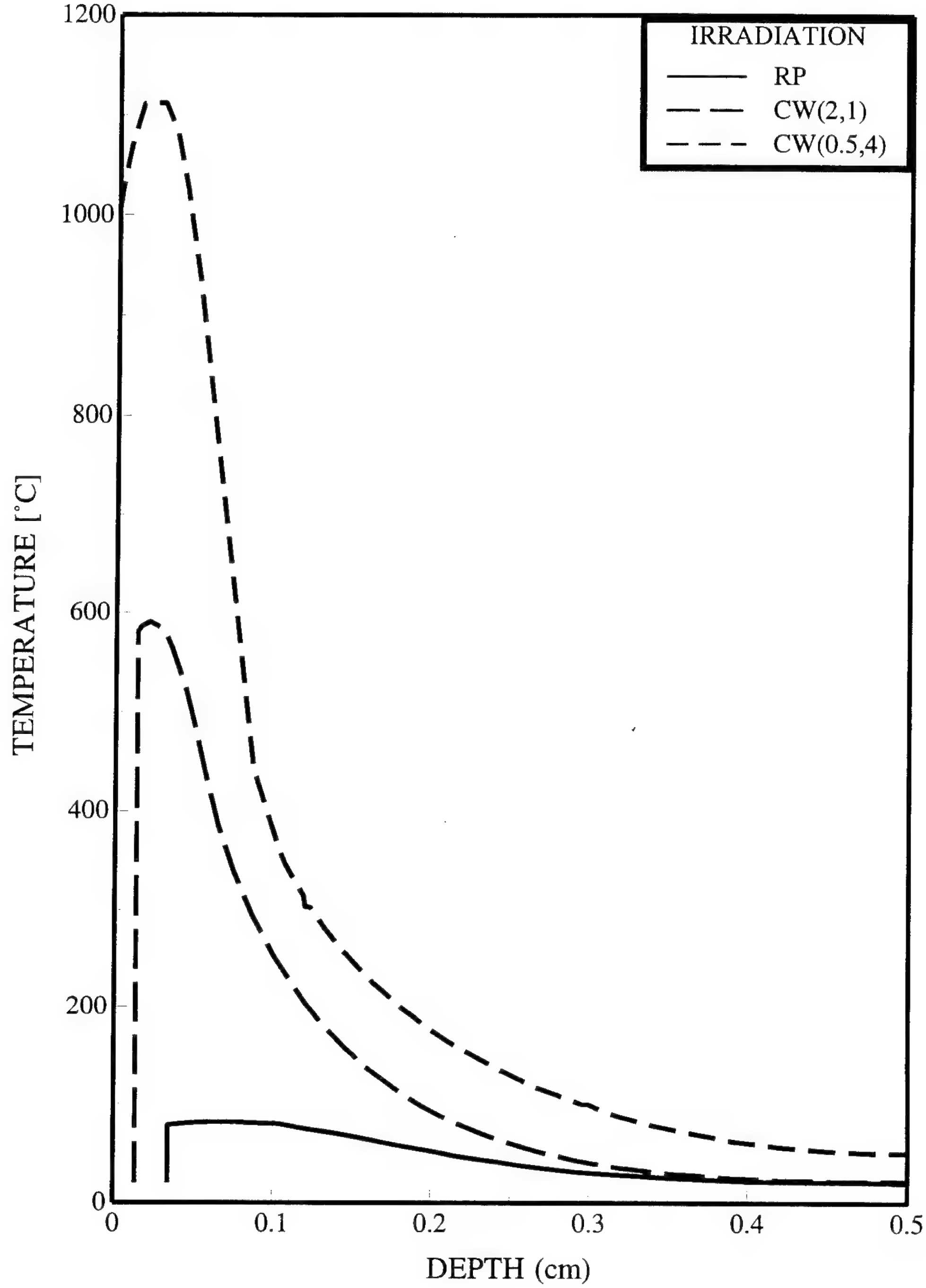

Fig. 9 — Temperature profiles in graphite\epoxy samples one second after the end of the irradiations

Results: Effects After the Irradiations

Figures 10-13 show the relative amounts of different forms of damage to the gr/ep caused by the different irradiations. Shown are ablation (ABL), complete pyrolization of the epoxy (CP), partial loss of the epoxy (PP), and loss of transverse tensile strength. The percentage numbers indicate the fraction of the nominal tensile strength present in that region of the sample at the given time after the irradiation. For example, the 70% number in the first bar in Fig. 10 indicates that from a depth of 0.55 mm to 0.95 mm the material possesses between 60% and 80% of its nominal transverse tensile strength. It is clear from Fig. 10 that the only significant damage done to the gr/ep by the RP irradiation was to ablate one third of a millimeter of the material. The bulk of the material never loses more that 20% of its nominal tensile strength.

The CW(2,1) irradiation has a much more dramatic effect, as can be seen in Fig. 11. More of the material is significantly damaged by either ablation or pyrolysis, and the bulk of the material has its tensile strength reduced to 60-80% of the nominal value for a prolonged period after the irradiation. (The simulations only followed the histories of the sample for 20 seconds after the end of the irradiations. Given the low thermal conductivity of the gr/ep, it would take a long time for the front surface cooling to remove the energy stored in the material.) The effects of the CW(0.5,4) irradiation are even more dramatic, as shown in Fig. 12. Considerably more of the material is significant damaged by pyrolysis, although there is no ablation, and after 20 seconds the bulk of the material has only 20-40% of its nominal strength. Most interesting is the fact that the material continues to weaken for at least 20 seconds after the end of the irradiation.

As a further contrast of ablating damage versus heating damage, Fig. 13 represents the effects of a 0.5 kW/cm^2 irradiation of the gr\ep for one second. This irradiation imposes only one quarter as much energy on the sample, but because the temperature of the sample never reaches the graphite fibers sublimation temperature, all of the energy goes into heating the sample. If we compare Figs. 11 and 13, we see that the damage in the two cases is similar, except there is no ablative damage in the second case.

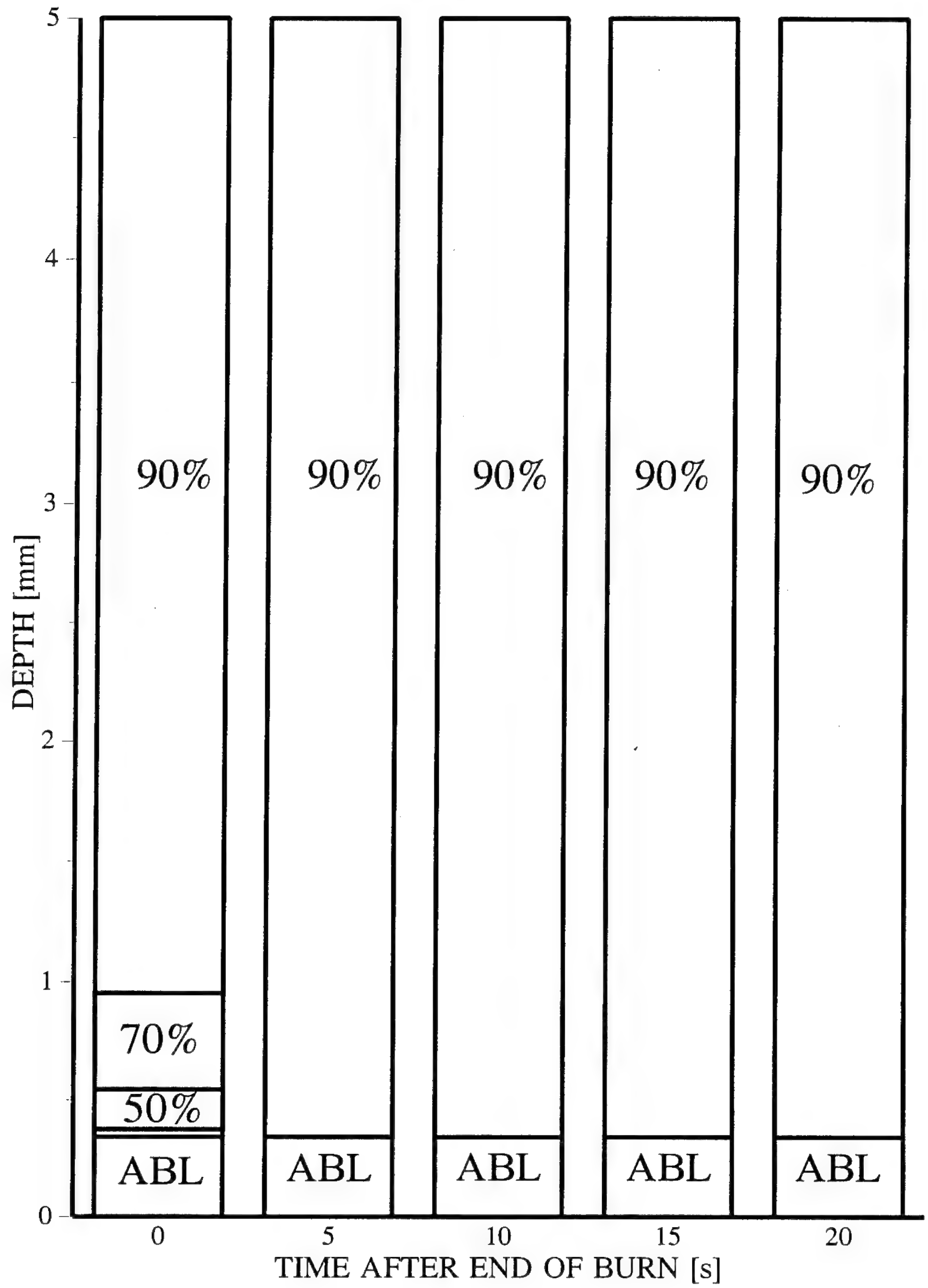

Fig. 10 — Time dependent damage to graphite\epoxy after a RP irradiation
[ABL = ablated; CP = completely pyrolyzed; PP = partially pyrolyzed; percentages indicate the fraction of nominal transverse tensile strength present]

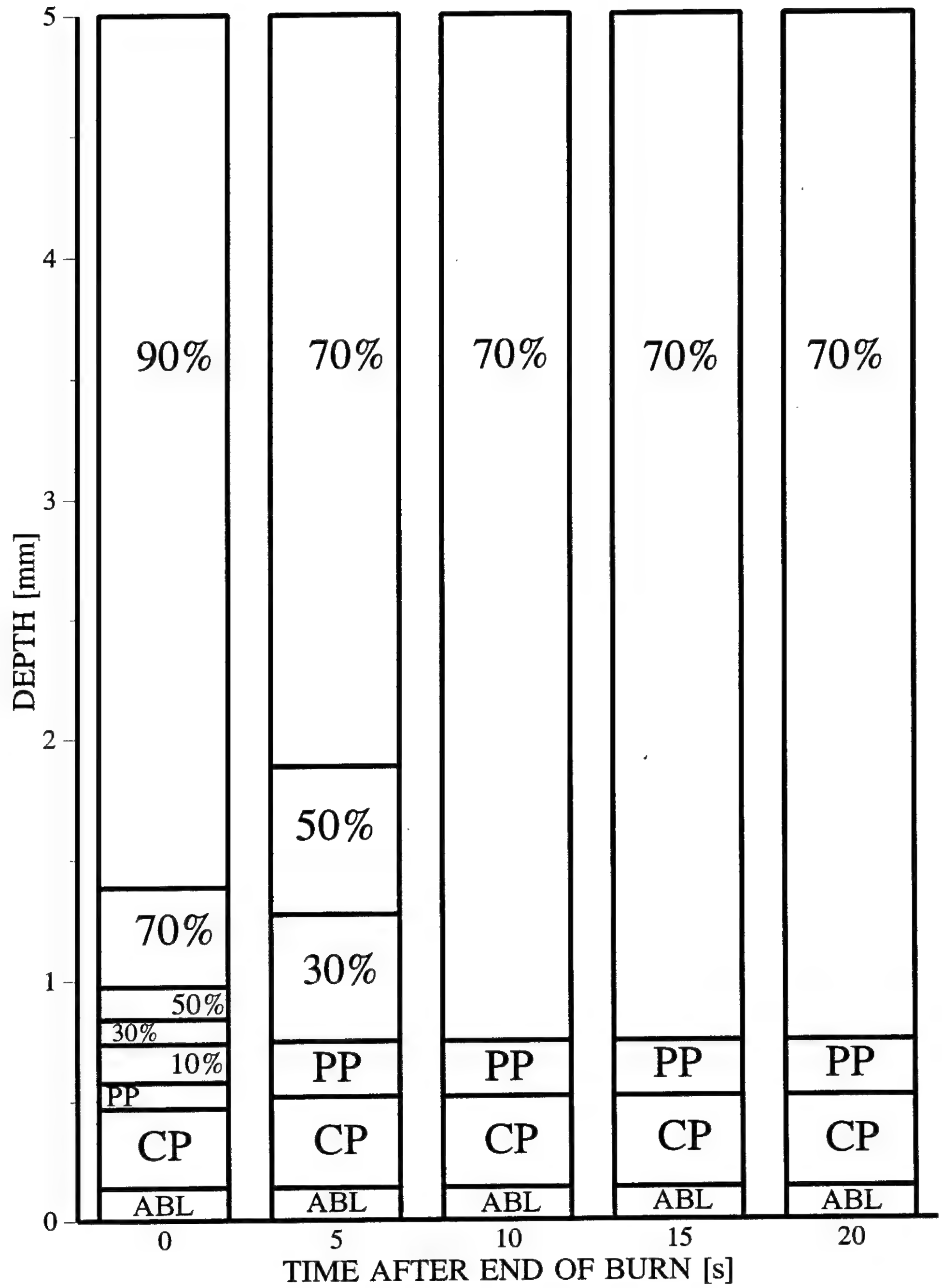

Fig. 11 — Time dependent damage to graphite\epoxy after a CW irradiation of $2\ kW/cm^2$ for 1 second
[ABL = ablated; CP = completely pyrolyzed; PP = partially pyrolyzed; percentages indicate the fraction of nominal transverse tensile strength present]

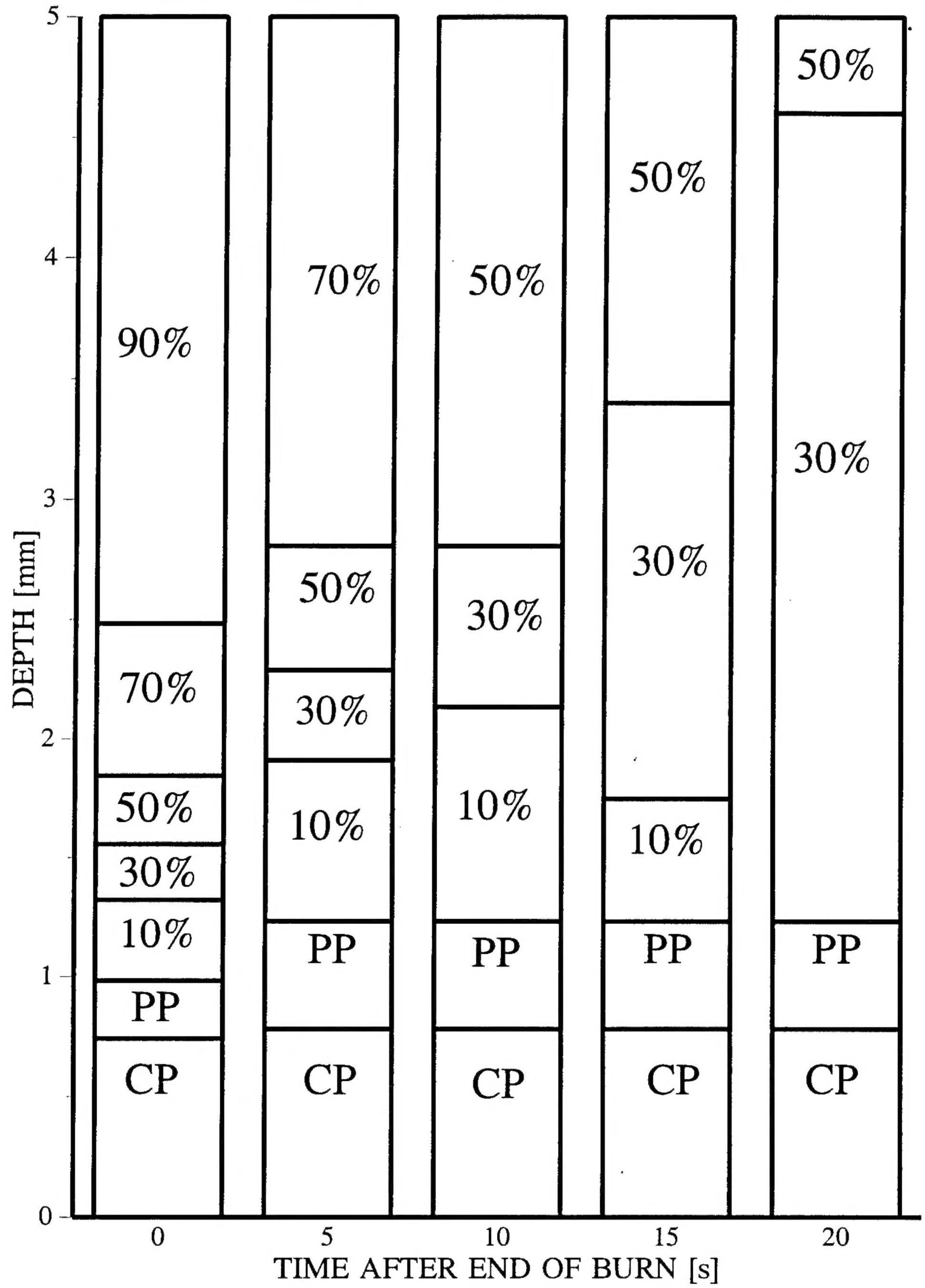

Fig. 12 — Time dependent damage to graphite\epoxy after a CW irradiation of 0.5 kW/cm^2 for 4 seconds
[ABL = ablated; CP = completely pyrolyzed; PP = partially pyrolyzed; percentages indicate the fraction of nominal transverse tensile strength present]

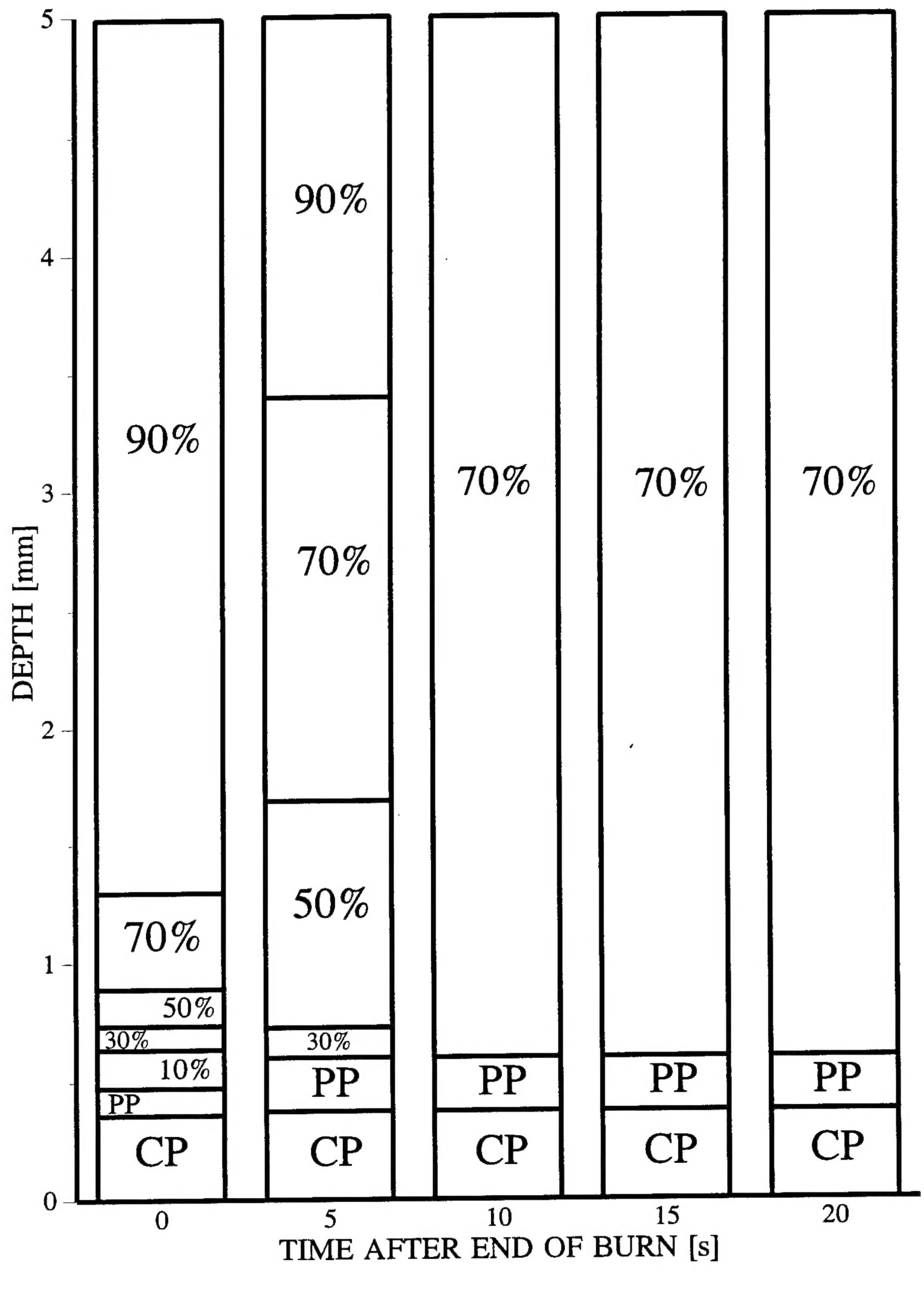

Fig. 13 — Time dependent damage to graphite\epoxy after a CW irradiation of 0.5 kW/cm^2 for 1 second

[ABL = ablated; CP = completely pyrolyzed; PP = partially pyrolyzed; percentages indicate the fraction of nominal transverse tensile strength present]

Conclusions

As we have detailed above, a great many simplifying assumptions adopted for these simulations. The most restrictive was treating the graphite/epoxy one-dimensionally, so that the loss of fiber chunks could not be modelled. There is also considerable uncertainty in the best values of absorption coefficients to use for the two materials.

Having said that, we assert that the major conclusions that we have reached do not depend on these assumptions. When comparing the two materials the crucial difference between the composite and the metal is the two order-of-magnitude difference in their thermal conductivities. When comparing the RP and CW irradiations, the crucial difference is the three order-of-magnitude difference in the instantaneous peak power that is introduced on the surface of the target sample.

These major conclusions are:

> Laser damage to aluminum depends almost entirely on the total average energy per unit area imposed on the sample, independent of the detailed nature of the laser irradiation.
>
> The aluminum is weakest at the end of the irradiation; it regains some of its tensile strength as it cools.
>
> The effect of a laser on graphite/epoxy depends intimately on the beam characteristics. Repetitively pulsed, high-peak-power beams remove surface material, but leave little remaining energy in the material. CW, low-peak-power beams deposit energy into the material surface, after which it gradually soaks into the depth of the material.
>
> The graphite/epoxy samples may be at their weakest (lowest transverse tensile strength) 20-30 seconds after the end of the irradiation.

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